



Analysis

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Mapping global freshwater ecosystems to guide national restoration targets and nature-based solutions

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Freshwater ecosystems regulate the water cycle, support biodiversity and enhance resilience, yet they remain largely overlooked in global climate policies, and most national commitments lack clear, spatially defined targets for their protection and restoration. Here our global map—derived from 30-m land-cover classification, hydrological networks and floodplain models—reveals around 51 million km² of rivers, wetlands, headwaters, riparian buffers and floodplains that are critical for water security and disaster risk reduction. Overlaying this map on country members of the Freshwater Challenge, we discuss pathways for integrating freshwater ecosystems into nature-based solutions for climate adaptation and mitigation. Furthermore, by analysing areas where forest would naturally occur within our mapped categories, we show that reforesting degraded croplands and short vegetation could sequester 1.07 and 3.41 gigatonnes of CO₂ per year, across 355–484 million hectares. These results provide a practical foundation for aligning global climate goals with regional freshwater targets.

Freshwater ecosystems play a fundamental role in regulating hydrological cycles, supporting biodiversity and maintaining climate stability¹. They provide essential services such as clean water supply, food production, flood regulation and carbon sequestration, yet they are among the most threatened ecosystems globally. Since 1900, wetland extent has declined globally by nearly 70%, only 37% of rivers longer than 1,000 km remain free-flowing over their entire length, and more than 50% of the world's rivers and streams are at high risks of pollution^{2,3}. Freshwater vertebrate populations have also suffered an 84% decline between 1970 and 2016⁴. Climate change intensifies these issues, leading to extreme rainfall variability, droughts and heatwaves⁵. Today, water-related disasters account for 90% of all natural disasters and are becoming increasingly frequent and severe⁶. By 2050, extreme droughts could impact five times more land globally,

5.7 billion people may experience water scarcity and 1.6 billion could be at flood risk⁷. These growing challenges have exposed gaps in reliable access to clean water, flood regulation and food production for millions of people^{2,8}.

Despite their critical role in biodiversity, climate resilience and water security, freshwater ecosystems have long lacked a systematic and unified global approach to restoration and conservation. The country-led Freshwater Challenge (FWC) was launched at the 2023 United Nations Water Conference to help close this gap. The FWC aims to restore 300,000 km of rivers and 350 million hectares of wetlands by 2030, aligning with global targets such as the Kunming–Montreal Global Biodiversity Framework's 30×30 goal. The initiative positions freshwater ecosystems at the heart of global environmental commitments and emphasizes that restoration efforts must be integrated with

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broader climate strategies, including those under the United Nations Framework Convention on Climate Change⁹.

However, achieving this integration remains challenging, particularly in countries of the global south. While 49 countries and the European Union have joined the FWC (as of May 2025), many still need to demonstrate meaningful progress in aligning freshwater restoration efforts with their Nationally Determined Contributions (NDCs) (country-specific climate action plans, outlining targets and measures for reducing greenhouse gas emissions and adapting to climate impacts) and National Adaptation Plans (NAPs) (country-level strategies that identify medium- and long-term adaptation needs and outline measures to address climate vulnerabilities; see Supplementary Table 1 for all acronyms). Freshwater ecosystems remain underrepresented in national climate strategies and biodiversity strategies, with references to rivers and wetlands often lacking spatial detail and actionable commitments¹⁰. Even where political will exists, countries frequently lack robust methodologies and spatial datasets to define coherent, measurable restoration targets that can be effectively linked to climate adaptation under NAPs. While the carbon dynamics of freshwater systems are increasingly well understood^{11,12}, including their roles in both greenhouse gas storage and emissions, carbon markets have historically focused on terrestrial forests. Although riparian and headwater forests are technically part of terrestrial ecosystems, they provide essential ecological services that support freshwater function. These freshwater-adjacent landscapes offer both carbon sequestration potential and hydrological benefits, yet they remain a largely untapped opportunity within integrated nature-based climate solutions.

To address these gaps, we develop a spatially explicit framework to guide the prioritization of protection and restoration actions for high-value freshwater ecosystems (HVFEs), including headwater catchments, riparian zones and floodplains. Using case studies from FWC countries, we illustrate how this approach can support geographically specific, policy-relevant targets aligned with national climate strategies such as NDCs and NAPs. The framework emphasizes ecological integrity by prioritizing natural regeneration in forest biomes and avoiding ecologically unsuitable afforestation or wetland conversion^{13,14}. By applying this framework, we assess the global carbon sequestration potential of restoring degraded lands near freshwater systems, highlighting the dual adaptation and mitigation benefits of integrated, ecosystem-based strategies.

Assessing the global distribution of HVFEs

We adapted the High Conservation Value framework¹⁵—an internationally used approach for identifying areas with exceptional ecological or social value, originally developed for sustainable land management—to define HVFEs, aiming to support a more strategic and actionable approach for identifying freshwater ecosystems in need of conservation (including both protection and restoration). HVFEs extend beyond conventional freshwater definitions by integrating freshwater and adjacent terrestrial ecosystems that collectively support the regulation of hydrological and carbon cycles within watersheds. These ecosystems include headwater catchments, surface water bodies (for example, rivers, lakes and reservoirs), riparian corridors, inundated wetlands and geomorphic floodplains (areas shaped by long-term river activity and landform development, rather than by short-term flood frequency). Together, they exert a disproportionate influence on global water flow, filtration and storage, as well as nutrient and carbon dynamics. Moreover, they serve as vital refugia for aquatic and terrestrial biodiversity. Existing freshwater classifications often overlook the full extent of the terrestrial interface—particularly riparian and floodplain systems—that sustains freshwater ecosystem services. Thus, identifying HVFEs allows a more comprehensive and ecologically meaningful delineation of priority areas for conservation and restoration, critical for achieving targets under initiatives like the FWC. Restoration action for FWC will

need to restore one or more degraded key ecological attributes such as hydrologic regime, connectivity, water quality, physical habitat and biotic composition¹⁶. This includes forested zones adjacent to rivers and wetlands that improve lateral connectivity, enhance water quality, stabilize banks and support riverine biodiversity, making them essential to both forest and river restoration efforts.

We developed a high-resolution global map of HVFEs to support actionable conservation strategies. The map, produced at 30-m resolution, captures freshwater-related features under two delineation scenarios (minimum and maximum), reflecting a range of conservation approaches based on ecosystem service capacity. This delineation draws on foundational global datasets, including the University of Maryland (UMD) land cover and land use change dataset¹⁷, 90-m hydrography data derived from Multi-Error-Removed Improved-Terrain (MERIT) Hydro digital elevation model¹⁸ and global floodplain layers¹⁹, to ensure consistency and spatial precision across diverse landscapes.

The minimum scenario includes surface water bodies, wetlands, headwater regions and fixed-width riparian corridors along low-order and high-order streams. It also includes riparian buffers surrounding lakes and reservoirs. This conservative delineation focuses on preserving water quality, reducing erosion and maintaining aquatic habitats. The maximum delineation scenario builds upon this foundation by incorporating geomorphic floodplains and wetland corridors, extending delineation further into broader hydrological zones. Geomorphic floodplains refer to fluvial landforms shaped over long timescales by river processes such as sediment deposition, lateral migration and channel meandering—rather than by short-term inundation frequency—and thus represent stable features suitable for long-term restoration¹⁹. This scenario emphasizes flood mitigation, sediment retention and long-term water storage capacity, recognizing the full hydrological and ecological role of floodplains and their relevance to the functioning of the entire river network. Importantly, including these floodplain zones enhances climate mitigation potential by expanding the extent of persistent carbon reservoirs in restorable ecosystems²⁰. These reservoirs include riparian forests and other aboveground biomass, as well as organically rich soils formed through cyclical flooding and drying—processes that contribute substantially to long-term carbon storage²¹. Including the geomorphic floodplains in the maximum delineation scenario (see ‘Assessing climate mitigation benefits’ section) yields a carbon sequestration potential of 3.41 GtCO₂ yr⁻¹, in part by leveraging the sink capacity of floodplain-adjacent reforestation. As expected, this broader delineation overlaps with and masks riparian corridors and headwater regions defined under the minimum footprint scenario, consistent with the hierarchical masking rules (Supplementary Methods B). These two delineation scenarios—with and without floodplain inclusion—correspond to the maximum and minimum HVFE extents shown in Fig. 1.

The global map in Fig. 1 reveals that HVFEs, under the maximum delineation scenario, span approximately 51.6 million km² globally. The highest concentrations of HVFEs are found in countries with extensive river networks and wetlands. The Russian Federation holds the largest area (8.68 million km²), followed by Canada (4.80 million km²), the USA (3.99 million km²), China (3.67 million km²) and Australia (3.35 million km²). Other major contributors include Brazil (2.92 million km²), Argentina (1.39 million km²), India (1.38 million km²) and Kazakhstan (1.25 million km²). Notably, the 49 countries that are members of the FWC collectively account for 22.9 million km², or approximately 44% of the global HVFEs extent under the maximum scenario (with floodplain). If Russia and China were to join the initiative, this share would rise by an additional 12.3 million km², increasing the total coverage to approximately 68% of all HVFEs. These figures underscore both the global relevance of the HVFE framework and the substantial opportunity to enhance global conservation efforts through expanded participation in the FWC. Under the minimum scenario, HVFEs cover 40.9 million km², meaning the 10.7 million km² difference between scenarios highlights

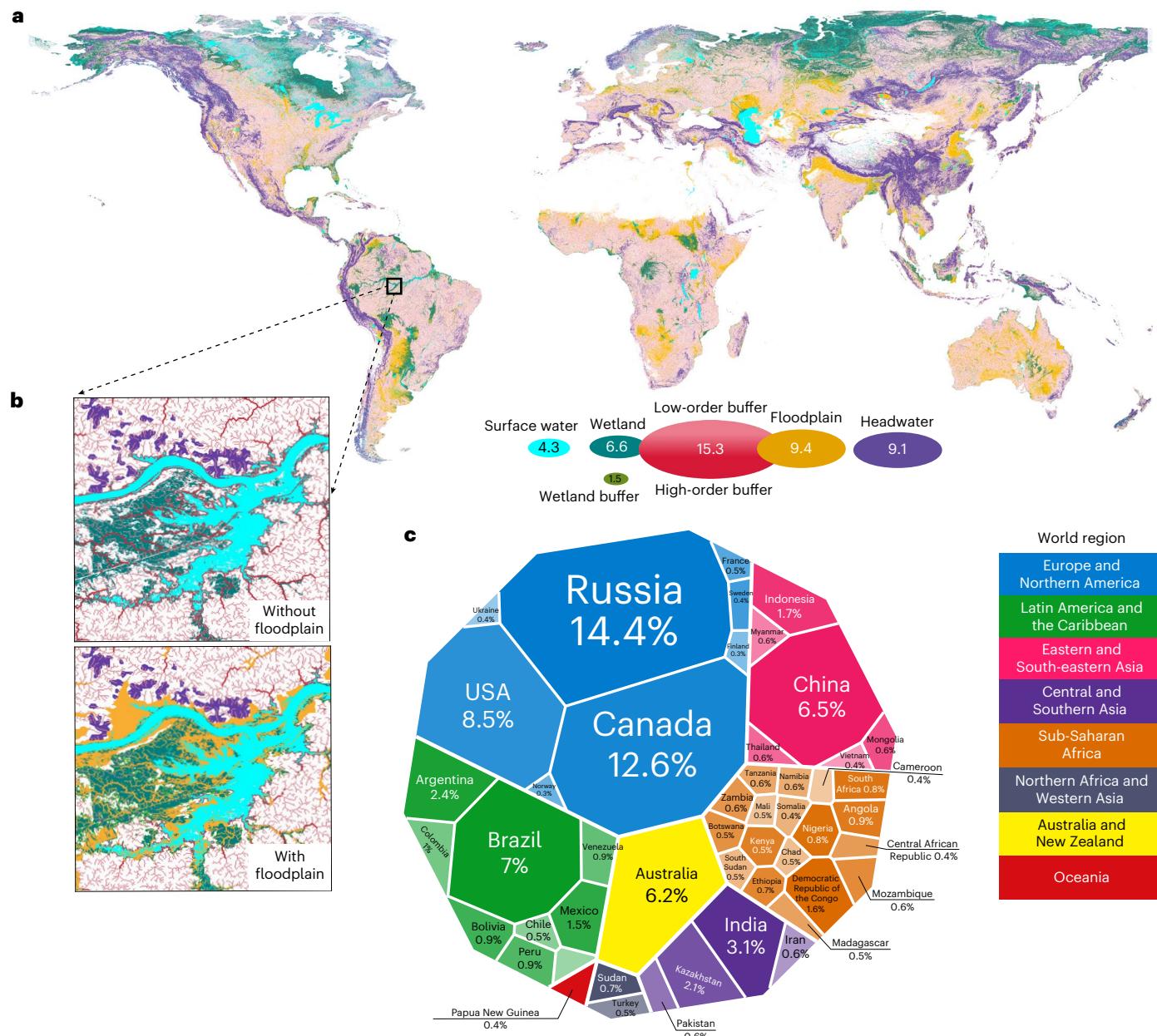


Fig. 1 | Global distribution and delineation of HVFEs. **a**, Global map of HVFEs under the maximum delineation scenario, showing surface water bodies (rivers, lakes and reservoirs), headwater catchments, regularly flooded wetlands, geomorphic floodplains and fixed-width riparian corridors along low-order and high-order streams. Bubble sizes in the legend represent the global area of each HVFE component in million km². **b**, Comparison of the maximum and minimum

HVFE delineation scenarios (with and without floodplain). **c**, Top 50 countries ranked by the extent of fixed-width riparian corridors around high-order streams and lakes, representing the maximum possible buffer coverage within the HVFE framework. Percentages indicate each country's contribution to the global total, with color coding representing different world regions.

the importance of including geomorphic floodplains and wetland corridors in conservation planning. However, this difference is not entirely attributable to floodplains alone, as partial overlap exists between floodplain zones and riparian or wetland areas captured in the minimum scenario (Fig. 1). A detailed breakdown of HVFE components under each delineation scenario is provided in Supplementary Table 2.

To support local adaptation and ensure the global HVFE map is useful across diverse geographies, we validated the mapping approach in the contiguous USA (CONUS), which offered the only available riparian reference data, along with ecological variability (for example, climate, vegetation and hydrology). In addition to this empirical validation, the foundational datasets underlying the HVFE framework—including UMD land use and land cover change dataset¹⁷, MERIT 90-m hydrography

data¹⁸ and global floodplain layers¹⁹—have each undergone independent validation, further supporting the robustness of the approach (Supplementary Methods A and D).

Identifying freshwater-related ecosystem adaptation strategies

Despite their essential role in climate regulation, biodiversity support and water security, freshwater ecosystems remain underrepresented in most NDCs²² and NAPs. References to water often focus on general hazards such as droughts and floods, without spatially explicit targets or actionable strategies. Although there is growing recognition of the synergies between adaptation and mitigation—particularly across water, land and biodiversity sectors²³—key freshwater systems, including

	Measures and actions		Key impacts: flow and water quality regulation; ecosystems of cultural and spiritual significance; essential for arresting declines in freshwater biodiversity
	Protection	Restoration	
Riverine, lacustrine and wetland ecosystems	Maintain environmental flows; fishing and mining regulations; inclusion in protected areas and OECMs	Restore connectivity along the river system and with floodplains/wetlands; remove/control damaging invasive species	
Floodplains and fixed-width corridors	Introduce and/or enforce zoning and building codes in natural floodplains and near freshwater ecosystems	Restore ecosystems, such as riparian forests, within locally defined buffers and/or within natural floodplains	Key impacts: flood, sediment and nutrient regulation; climate connectivity corridors for species movement and adaptation to climate change; habitat for pollinators
Headwater regions	Inclusion in and management of protected areas and critical water source protection	Restore degraded ecosystems for improved green cover; to native vegetation (ecological restoration) or agroforestry (ecosystem restoration)	Key impacts: water supply regulation and soil erosion control

Fig. 2 | Examples of protection and restoration measures to safeguard freshwater-related ecosystems. Each row represents a group of HVFE categories. The columns of protection and restoration list a set of measures of action that could be aligned with these categories to define spatially explicit and

quantified targets for NAPs, among others. The final column of key impacts is illustrative of the key services supported and expected impacts. Credit: ecosystem illustration elements, [Canva.com](https://canva.com).

headwaters, riparian corridors and geomorphic floodplains, continue to be overlooked relative to coastal ecosystems such as mangroves¹⁰. Realizing the full potential of NDCs and NAPs will require spatial frameworks and decision-support tools that directly align climate goals with freshwater ecosystem functions.

We propose using the HVFE framework to translate these ambitions into informed, holistic nature-based actions. While HVFEs represent ecologically important freshwater and adjacent ecosystems, we explicitly integrate them with UMD land use and land cover change dataset to identify degraded areas—such as croplands and short vegetation—within these systems. This enables the framework to reflect actual land condition, not just ecological potential, and to spatially target areas where restoration is both needed and feasible.

This integration supports countries in identifying spatially defined pathways that align freshwater interventions with known climate adaptation and mitigation benefits, positioning freshwater ecosystems as foundational assets for climate action. Figure 2 presents a set of measures across HVFE categories and highlights the key ecosystem services each supports. These actions fall into two main categories—protection and restoration—based on the multiple benefits freshwater ecosystems offer, including safeguarding water resources, supporting biodiversity and building resilient livelihoods²⁴.

Under the category of protection, countries can regulate environmental flows (the quantity, timing and quality of freshwater flows required to sustain ecosystems and human livelihoods), restrict harmful resource extraction (for example, fishing and mining) and designate freshwater protected areas or Other Effective Area-Based Conservation Measures (OECMs). For example, Nepal, with over 36% of its land in headwater regions and a high projected flood risk by 2050²⁵ (Aqueduct score: 3.8 on a 0–5 scale; Supplementary Table 3), faces heightened climate threats. Proactive management—such as safeguarding upstream ecosystems, enforcing flow regulations (for example, maintaining

minimum environmental flows, regulating seasonal water releases and limiting upstream diversions) and strengthening zoning in headwater catchments—can help protect downstream communities and maintain ecosystem function.

Under the category of restoration, actions may include reconnecting rivers with floodplains, restoring riparian forests and rehabilitating degraded vegetation in headwater regions to improve green cover and reduce erosion. Countries such as Mozambique, Pakistan and Malawi present high-impact opportunities for restoration. For instance, Mozambique, with a flood risk score of 4.1 (on a 0–5 scale, based on the Aqueduct Floods hazard index, which incorporates hydrological modelling and exposure data to estimate projected flood risk by 2050)²⁵ and 6.2 million hectares of cropland expansion into tree cover, wetlands and other natural land covers between 2000 and 2020 (Fig. 3), can prioritize restoration in degraded floodplains and upper watersheds to enhance water retention and reduce erosion. Similarly, Pakistan, with 21% of its land classified as geomorphic floodplains and a flood risk score of 3.25, represents a strong candidate for riparian buffer restoration to improve flood resilience in vulnerable basins. For example, the devastating 2022 floods in Pakistan (which affected over 33 million people and submerged a third of the country²⁶) and their recurrence in 2025 underscore the critical importance of restoring floodplains and riparian buffers to mitigate future disasters. Given that around 20% of Malawi's landscape consists of riparian corridors and floodplains—and with one of the highest projected flood risk scores by 2050 (4.1 on a 0–5 scale)—the country presents a strong opportunity for floodplain reconnection and riparian forest restoration.

By guiding countries in selecting geographically tailored and ecologically appropriate interventions, the HVFE framework supports the design of integrated, ecosystem-based strategies that simultaneously advance adaptation, mitigation and biodiversity goals.

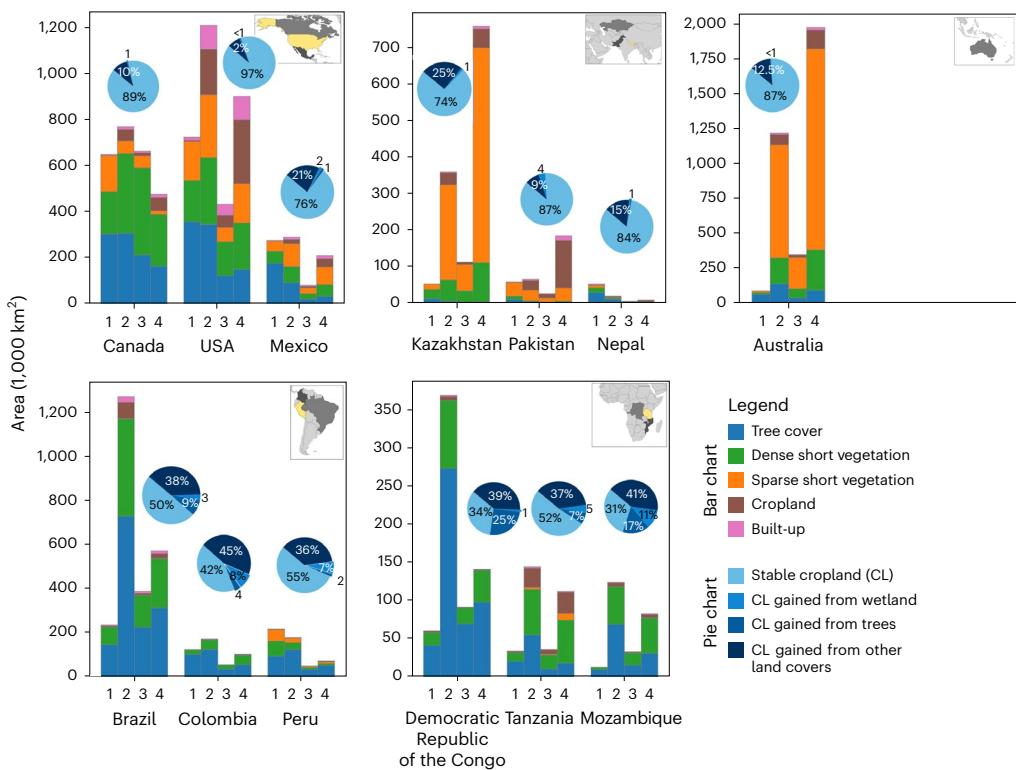


Fig. 3 | Land cover composition and cropland transformation across HVFE types in 13 FWC countries. This figure shows the land cover distribution for each country across four HVFE classes—class 1 (headwater regions), class 2 (fixed-width corridors around first-order streams), class 3 (corridors around higher-order streams and lakes) and class 4 (geomorphic floodplains)—based on UMD land use and land cover change data from 2000 to 2020. Stacked bars

represent current land cover (in 1,000 km²) per HVFE class, including tree cover, short vegetation, dense vegetation, cropland and built-up areas (a single class encompassing urban, industrial and other developed land; subcomponents not distinguished). Inset pie charts represent the cumulative cropland area across all four HVFE classes and the percentage of cropland gained from pre-existing tree cover, wetlands or other land covers.

Table 1 | Distribution of HVFE categories and restoration potential in six selected FWC countries

Country	Total HVFE area (ha, % of country)	Headwater (ha, % of HVFE)	Floodplain (ha, % of HVFE)	High-order stream buffer (ha, % of HVFE)	Low-order stream buffer (ha, % of HVFE)	Restoration opportunity (ha)	Percentage of FWC goal
Brazil	291,991,506 32.6%	2,357,981 8.1%	57,675,677 19.8%	1,542,4967 5.3%	114,630,036 39.3%	104,509,638	29.7
Pakistan	32,342,041 37.0%	5,961,769 18.4%	186,092,39 57.5%	1,312,758 4.1%	4,110,006 12.7%	32,064,772	9.1
Peru	60,338,198 46.6%	21,873,575 36.3%	7,325,185 12.1%	2,387,516 4.0%	16,332,939 27.1%	20,029,908	5.7
Democratic Republic of the Congo	81,824,353 35%	6,066,312 7.4%	14,196,578 17.4%	3,563,049 4.4%	33,487,428 40.9%	18,115,205	5.1
Mozambique	25,911,122 32.7%	1,293,732 5.0%	8,295,580 32%	1,115,629 4.3%	11,042,160 42.6%	12,778,794	3.6
Nepal	8,562,265 58.2%	5,305,164 62%	886,650 10.4%	371,098 4.3%	1,816,804 21.2%	4,488,788	1.3

Restoration opportunity refers to areas within HVFE-adjacent terrestrial ecosystems currently under cropland, urban land or dense/sparse short vegetation. ‘Percentage of FWC goal’ indicates each country’s potential contribution towards the global FWC target of restoring 300,000 km of degraded rivers (focusing on riparian corridors) and 350 million hectares of degraded wetlands by 2030.

Using HVFE mapping to prioritize strategies

The land cover composition and cropland transformation across four HVFE classes in 13 countries show that countries such as Brazil, Colombia, Democratic Republic of the Congo and Mozambique have experienced the most extensive cropland expansion in HVFEs between 2000 and 2020 (Fig. 3). Notably, 25% of cropland in Democratic Republic of the Congo replaced tree cover, while 27% in Mozambique originated from both tree cover and wetlands—indicating notable freshwater ecosystem degradation.

These types of patterns reveal critical restoration opportunities, particularly where cropland or short vegetation overlaps with HVFEs.

Reforestation or wetland recovery in such areas can enhance water infiltration, reduce erosion and improve water quality—offering measurable adaptation outcomes²⁷. These spatial insights can be useful for countries to translate freshwater restoration ambitions into actionable, place-based ecosystem interventions.

To further illustrate region-specific pathways of action, we analysed the detailed breakdown of HVFE types and their restoration potential across six case-study countries (Table 1): Nepal, Pakistan, Mozambique, Democratic Republic of the Congo, Brazil and Peru. These examples span different HVFE types (for example, headwaters, floodplains and stream buffers) and climate risks and the isolation of

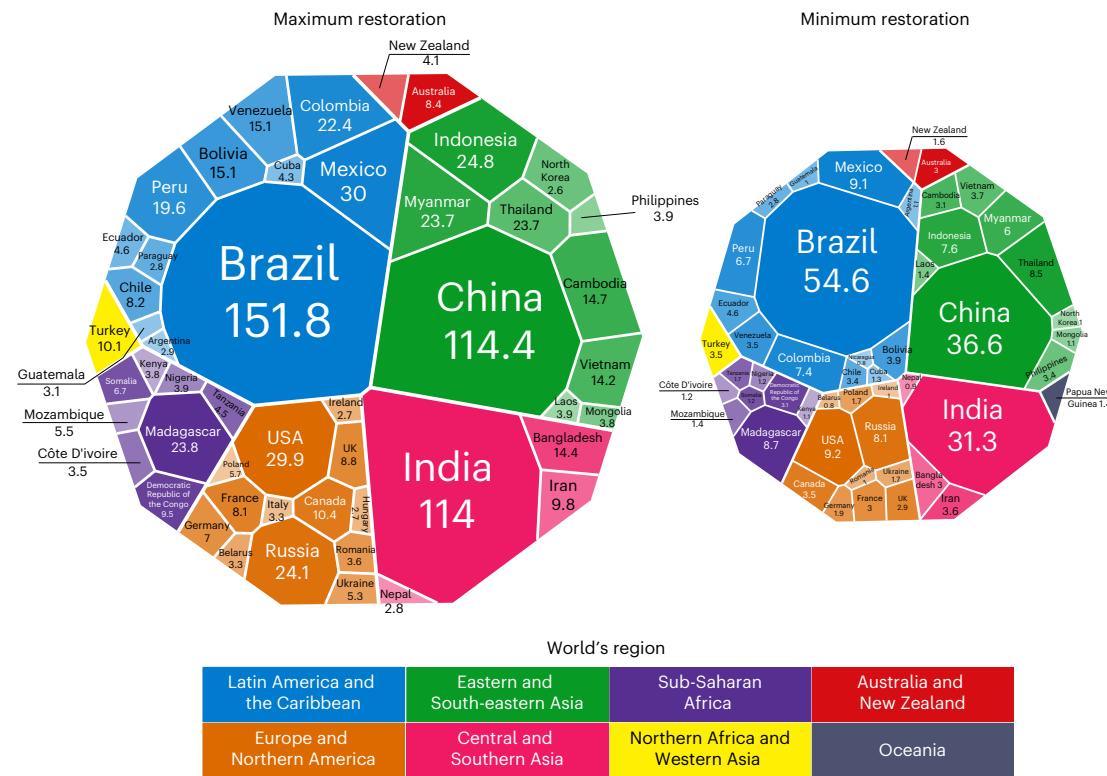


Fig. 4 | Annual CO₂ removal potential (TgCO₂ yr⁻¹) across the top 50 countries under maximum and minimum restoration scenarios. The size of each country's potential is scaled according to the total global potential. Numbers indicate each country's contribution to the global total, in TgCO₂ yr⁻¹, with color

coding representing different world regions. The minimum scenario includes surface water bodies with riparian buffers, wetlands, headwater regions and fixed-width riparian corridors along streams. The maximum scenario adds geomorphic floodplains and wetland corridors.

the cropland change relative to the HVFE classes, which elucidates more straightforward restoration targets and allows clearer recommendations for both protection and restoration strategies under the HVFE framework (see Supplementary Fig. 1 for HVFE maps and Supplementary Table 4 for a detailed breakdown of land cover composition across the full set of 49 FWG countries under the maximum delineation scenario).

In Nepal, headwater regions remain largely intact (Table 1), offering an opportunity for proactive protection through zoning regulations, water source protection and integration into OECMs. These approaches align with the country's National Water Resources Policy (2020), which promotes watershed management and river basin planning for sustainable water resource use²⁸, as well as ongoing initiatives focused on spring and watershed restoration in upland areas²⁹. Furthermore, Nepal has formally recognized OECMs—including community-managed forests and sacred sites—as part of its broader strategy to conserve biodiversity and ecosystem services beyond traditional protected areas³⁰. Maintaining these upstream buffers is critical for reducing downstream flood risk in the Terai region, where communities face some of the country's highest flood-related vulnerabilities³¹.

Similarly, in Democratic Republic of the Congo, riparian corridors still retain substantial tree cover and natural vegetation, supporting both freshwater storage and diverse fish populations that are crucial for local livelihoods and climate resilience^{32,33}. Prioritizing protection and sustainable management in these areas can help maintain rainfall recycling and the health of aquatic ecosystems. Notably, with 25% of recent cropland expansion replacing tree cover, these same areas could also be prioritized for restoration efforts to reverse freshwater ecosystem degradation.

In parts of Peru, headwater regions along low-order streams retain substantial forest cover, highlighting opportunities for early intervention through conservation easements and Indigenous-led land

management in the Andes–Amazon transition zone^{34,35}. Areas of short vegetation offer restoration potential; however, cropland expansion is increasingly encroaching on riparian corridors and floodplains, underscoring the need for both protection and restoration.

By contrast, other countries exhibit more advanced ecosystem degradation, where restoration is a more urgent priority. In Pakistan, extensive cropland encroachment into floodplains has reduced flood-buffering capacity, especially in the Indus Basin³⁶. Restoration through riparian reforestation and floodplain reconnection to rivers could mitigate these risks. In Mozambique, nearly 70% of cropland expansion between 2000 and 2020 replaced tree cover, wetlands and other natural land covers—primarily within floodplains and low-order stream buffers (Fig. 3). Recent studies suggest that wetland function—including hydric soil properties—can persist for years following conversion to agriculture, particularly when conversion is recent, making such areas more responsive to restoration³⁷. With high projected flood risk in regions such as Sofala Province, hydrologic reconnection and land use zoning are essential to prevent further loss³⁸. In Brazil, riparian corridors and floodplains have experienced extensive conversion—over 114,000 km²—from wetlands and forests to cropland, threatening the functionality of these critical ecosystems³⁹. Restoring riparian buffers and enforcing the Forest Code are vital for water regulation and strengthening climate resilience⁴⁰.

However, restoration activities should be designed with consideration of potential leakage effects—where restoring degraded land in one area could inadvertently shift agricultural expansion to more ecologically sensitive areas elsewhere. These risks highlight the importance of integrated land use planning and monitoring frameworks, including socioeconomic safeguards, to ensure that restoration leads to net ecological benefits rather than displacement.

Altogether, these case studies demonstrate how HVFE maps can help align restoration, protection and improved management of

freshwater ecosystems with climate adaptation needs at the national level. By linking HVFE conditions with spatial risk layers (for example, flood risk maps, water stress layers (defined as the ratio of water withdrawal to available renewable supply⁴³) and drought vulnerability zones), countries can identify high-impact interventions, refine NDC and NAP strategies, attract climate finance and monitor adaptation outcomes. Notably, many of these adaptation measures also offer mitigation co-benefits. Restoring HVFE can not only contribute to improved climate resilience but also increase carbon sinks.

Next steps could include developing implementation roadmaps, strengthening local capacity and integrating HVFE-based targets into national investment and monitoring systems, as highlighted in recent implementation and investment planning frameworks for ecosystem restoration and resilience.

Assessing climate mitigation benefits

To strengthen integration of freshwater-related ecosystem restoration targets (such as those to be developed by the state-members in FWC) and carbon mitigation commitments in NDCs, we have mapped the mitigation potential globally of reforesting degraded terrestrial ecosystems within HVFE delineation (of 'Assessing global distribution of HVFEs' section) in areas where forests would be the natural cover. Reforestation within HVFEs could provide 1.07–3.41 GtCO₂ yr⁻¹ of mitigation across 355–484 million hectares, depending on the scenario used (with 1.07 GtCO₂ yr⁻¹ representing the minimum and 3.41 GtCO₂ yr⁻¹ the maximum potential, based on differing delineations and tree cover thresholds; see 'Restoration potential in freshwater-adjacent terrestrial ecosystems' and 'Carbon removals from restoration'). The mitigation potential of the minimum scenario is approximately equivalent to that of global peatland restoration, while the maximum restoration scenario is slightly over half the potential of reducing global deforestation⁴¹. Figure 4 compares the total carbon removal potential for the top 50 countries, based on reforestation of areas where HVFEs currently exist in croplands or short vegetation—indicating abandoned agricultural or grazing land—within forest biomes under the minimum and maximum restoration scenarios. While Fig. 4 emphasizes total mitigation potential, the corresponding per-hectare carbon removal rates are provided in Supplementary Table 5 to support comparison of restoration efficiency across countries.

Large countries dominate the top five in terms of total mitigation potential—Brazil, China, India, the USA and Mexico—contributing 48% of the global total under all scenarios. However, when adjusting for country size by evaluating carbon removal per hectare, we find a hotspot of mitigation potential in West and Central Africa, with the highest-ranking countries being Republic of the Congo, Liberia, Ghana, Nigeria and Côte d'Ivoire. These countries achieve average carbon removal rates of 9.7 MgCO₂ ha⁻¹ yr⁻¹ (minimum scenario) and 17.9 MgCO₂ ha⁻¹ yr⁻¹ (maximum scenario), nearly double the average of all other countries. Among the 49 FWC member states, reforestation of degraded HVFE-adjacent terrestrial ecosystems could deliver 0.43–1.28 GtCO₂ yr⁻¹ of mitigation across 128–155 million hectares of forest areas—representing nearly half of both the global mitigation potential and the total area restored under each scenario. Much of this forest restoration occurs in riparian corridors—vegetated areas along-side rivers—and aligns with the FWC target of restoring 300,000 km of rivers by 2030.

This spatially explicit assessment highlights how prioritizing both total and area-adjusted mitigation potential can align freshwater protection with global climate goals. The mitigation potential we identify within HVFEs (1.07–3.41 GtCO₂ yr⁻¹) accounts for 2.7–8.5% of current global emissions (~40 GtCO₂ in 2021) according to the Global Carbon Budget⁴². Given that the suggested carbon budget to limit warming to 1.5 °C is estimated at just 380 GtCO₂ from 2023 onwards, restoring areas adjacent to HVFEs could play a meaningful role in meeting emissions reduction targets. Notably, the upper end of our

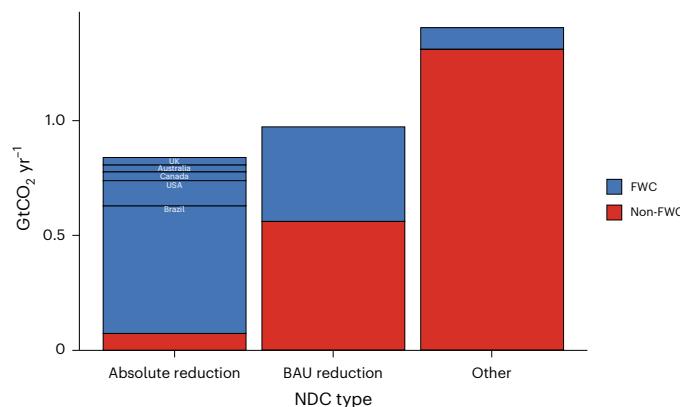


Fig. 5 | Comparison of climate mitigation potential (GtCO₂ yr⁻¹) from the maximum restoration scenario between countries committed and uncommitted to the FWC across NDC types. Three of the eight countries committed to the FWC and with absolute reduction NDCs (Norway, Moldova and Tajikistan) were not included in this figure because their mitigation potential (as defined in this study) is negligible. NDC types included in the 'Other' category are gross domestic product (GDP) intensity reduction, actions only, trajectory target, BAU not specified, per capita intensity reduction, cumulative emission target and unspecified. More information on these NDC types can be found in ref. 52.

scenario (3.41 GtCO₂ yr⁻¹) exceeds the estimated annual reduction of 1.4 GtCO₂ needed to reach net zero by 2050⁴²—underscoring the critical role that freshwater-adjacent ecosystem restoration can play in climate mitigation.

Climate mitigation commitments in NDCs can be conditional on external financing, unconditional or a mix of both. Among them, unconditional absolute reduction commitments—defined as firm emission cuts below a historical reference level, irrespective of economic or population growth—are considered the most ambitious. By contrast, business-as-usual (BAU) reduction commitments refer to emission targets relative to projected future growth trends, which may still permit annual emissions increases and are thus seen as less stringent.

Among the 32 countries with unconditional absolute emissions reduction targets, five FWC member states contribute approximately 92% of the total mitigation potential estimated within this subset (Fig. 5), regardless of restoration scenario (0.27 GtCO₂ yr⁻¹ minimum and 0.77 GtCO₂ yr⁻¹ maximum).

Mitigation potential from the reforestation of degraded HVFE-adjacent terrestrial ecosystems is highest in countries with gold-standard NDCs and is concentrated in these five nations. By contrast, countries with less stringent NDCs show a more diffuse and modest potential. These five countries thus represent a strategic opportunity to advance their climate goals through targeted restoration of HVFE-adjacent terrestrial ecosystems.

In order of decreasing potential, these are Brazil, the USA, Canada, Australia and the UK. By contrast, BAU reduction commitments, which are based on projected emissions growth, may still allow for year-on-year emissions increases and are therefore regarded as less ambitious. FWC countries with BAU-based targets contribute 42–44% of the total mitigation potential among all nations with such targets, under the minimum and maximum restoration scenarios, respectively (FWC $n = 22$; all $n = 71$). Compared with the maximum restoration scenario, the minimum scenario yields consistently a lower climate mitigation potential across all NDC types (Supplementary Fig. 2). The decline is particularly pronounced for FWC countries with absolute and BAU reduction commitments, underscoring how national-level contributions are highly sensitive to the assumed extent of HVFE-adjacent reforestation.

Although wetlands were excluded from our quantitative carbon modelling owing to global data limitations, recent meta-analyses and national-scale assessments indicate they may offer substantial mitigation potential. Schuster et al.⁴³ found that 77% of restored freshwater wetlands act as net carbon sinks, yet the full climate benefit—accounting for CO₂, CH₄ and N₂O emissions—takes an average of 141 years to materialize in non-peat systems. Reported sequestration rates also vary widely: Kayranli et al.⁴⁴ estimated that natural wetlands sequester approximately 0.03–0.3 kg C m⁻² yr⁻¹, while constructed wetlands can reach 1.5–2.2 kg C m⁻² yr⁻¹, although methane emissions can offset these gains. In addition, Roe et al.⁴¹ estimated that rewetted peatlands could sequester approximately 1,310 MtCO₂ yr⁻¹. As indicated, there is a substantial range in sequestration rates depending on the system and study. In the CONUS, Nahlik and Fennessy⁴⁵ estimated inland wetlands store 11.52 PgC, with degraded wetlands holding up to 171 tC ha⁻¹ less than least-disturbed sites. Although we did not quantify wetland restoration in our scenarios, these findings reinforce its complementary role in climate mitigation and highlight the importance of improving global datasets and quantification of carbon sequestration in wetlands to enable its future inclusion.

Conclusion

To meet the global demand for unified climate mitigation, freshwater ecosystems and their biological and hydrological functions—ranging from water supply and flood regulation to fish production and food security—must no longer be overlooked. Our global map, combined with metrics on ecosystem condition and mitigation potential, offers a critical foundation for systematically identifying, prioritizing, financing and implementing conservation, adaptation and restoration actions. In this way, by integrating freshwater and adjacent terrestrial ecosystems into national planning processes, we provide quantifiable benefits—including not only carbon sequestration but also improved ecosystem management—supporting a more coordinated global response and cascading restoration benefits. Importantly, this helps bridge the disconnect between freshwater action plans and plans addressing the climate and biodiversity crises. As global mapping methodologies are refined and informed by local ground-truthing, our ability to characterize ecosystems at the land–water interface—including wetlands, riparian zones, low-order streams and headwater catchments—will continue to improve. Notably, our results show that restoring degraded areas adjacent to freshwater ecosystems could sequester up to a maximum of 3.4 GtCO₂ yr⁻¹—equivalent to over 8% of global emissions—highlighting the powerful role that integrated restoration can play in advancing climate goals. By highlighting overlaps among these three global imperatives of climate mitigation, climate adaptation and freshwater ecosystem conservation, our Analysis aims to help harmonize global and local narratives—an essential step towards aligning freshwater ecosystems with climate action.

Methods

We assessed global forest restoration potential near freshwater ecosystems using a geospatial workflow built on the best-available, openly accessible global datasets (Supplementary Table 6). A schematic overview of the mapped HVFE features—including freshwater systems and adjacent terrestrial zones—along with detailed definitions, is provided in Supplementary Methods A. All features were classified and mapped at ~30-m spatial resolution, consistent with the land cover dataset used to evaluate restoration potential in this study.

Global delineation of HVFEs

The global HVFE layer consists of seven ecosystem classes, two of which—surface water and regularly flooded wetlands—represent core freshwater ecosystems. These were derived from the global land cover change dataset developed by Potapov et al.¹⁷, based on Landsat imagery spanning from 2000 to 2020. This dataset was selected for its capacity

to capture both seasonal and interannual dynamics of surface water bodies, as well as its detailed land cover classifications, which are critical for identifying forest restoration opportunities and estimating carbon accumulation potential. To reduce the uncertainty associated with transient surface water and wetland features in a static global map, we combined extents from both endpoints (2000 and 2020), thus representing long-term freshwater presence.

Accurate delineation of wetlands at a global scale remains challenging due to limited in situ validation data. As a result, the mapped freshwater classes in this product primarily reflect the presence of water at or near the surface and serve as proxies to identify adjacent terrestrial ecosystems that influence freshwater function. The remaining five HVFE classes represent terrestrial ecosystems closely linked to freshwater systems, serving as critical areas for restoration and protection to sustain local and downstream freshwater benefits. The integration of these seven classes into two composite layers (with and without the inclusion of floodplains) and the associated overlap logic are detailed in Supplementary Methods B.

Headwater catchments

To delineate headwater catchments, we identified first-order subcatchments with hydrologically active terrain. We utilized the MERIT Hydro subcatchment dataset (90-m resolution)¹⁸, which was downscaled to 30 m for consistency with the HVFE map. First-order subcatchments were extracted by overlaying the MERIT Hydro stream network (Strahler order 1) and applying a minimum slope threshold of 0.1 (−5.7°) to exclude flat, low-energy areas. This approach prioritizes regions likely to contribute meaningfully to streamflow and freshwater regulation at the watershed scale.

Fixed-width corridors and floodplains

Due to the absence of a globally consistent riparian mapping dataset, we delineated riparian corridors using a combination of fixed-width buffers and geomorphic floodplains to approximate zones suitable for restoration along streams, lakes and regularly flooded wetlands. Fixed-width buffers were applied to surface water features identified in the land cover dataset. Because these features may not represent a continuous hydrological network, we merged them using centerlines from the MERIT Hydro stream network to create a connected riverine system. Buffer widths were selected to reflect common policy or conservation standards, with justification for each width provided in Supplementary Methods.

Validation of riparian buffers was conducted in the CONUS using the USFS riparian dataset⁴⁶ (Supplementary Methods D), which provides 10-m-resolution reference data for comparison.

Unlike fixed-width buffers, floodplains are variable-width zones that follow the terrain and hydrological conditions associated with rivers and streams. We used the GFPLAIN90 dataset⁴⁷ to map geomorphic floodplains globally. Developed using the GFPLAIN v1.0 algorithm¹⁹ and the MERIT Hydro terrain model, GFPLAIN90 offers a high-resolution (90-m) representation of floodplain extents, using a minimum contributing area threshold of 20 km² to define stream networks. This dataset was selected for its scalability across diverse landscapes and hydrologic regimes.

Restoration potential in freshwater-adjacent terrestrial ecosystems

We calculated area available for restoration only within a targeted subset of the HVFE delineation described above, based on biome, HVFE class, delineation scenario and land use/land cover. These criteria are in place to avoid afforestation. We considered only areas within forest biomes, as defined by the RESOLVE 2017 vector dataset⁴⁸, to be available for reforestation. Within forest biomes, we used three HVFE classes included in both the minimum and maximum delineation scenarios: headwater regions, fixed-width buffers around low-order streams,

and fixed-width buffers around surface water bodies and high-order streams. In the maximum scenario, we additionally incorporated geomorphic floodplains, bringing the total to four HVFE classes used in the analysis. Finally, within these geographic criteria, we considered degraded or deforested areas as available for restoration, that is, crop-lands and short vegetation classes from Potapov et al.⁴⁹.

Carbon removals from restoration

We estimated carbon removals from restoring croplands and short vegetation using carbon accumulation rates from the first 30 years of natural forest regeneration, as mapped globally by Cook-Patton et al.¹³. This study modelled aboveground carbon accumulation rates globally at ~1 km² (at the Equator) resolution using 13,000+ field observations and a suite of environmental variables to predict rates of carbon accumulation per hectare per year up to 30 years. We adjusted the carbon accumulation rates for the headwater regions and fixed-width buffer around low-order streams in the minimum scenario (without floodplain) by multiplying them by the maximum optimal tree cover percentage in agricultural lands, as estimated by Sprengle-Hyppolite et al.⁵⁰. This adjustment was applied specifically to the minimum scenario to reflect minimal impact on agricultural production. These values were derived through an expert-elicitation process, identifying maximum tree cover thresholds for 53 regional cropping and grazing systems that safeguard agricultural yields⁵⁰.

Following this adjustment to the carbon accumulation rates, we calculated summary statistics using Google Earth Engine (see 'Code availability' section). Country-level and global totals were derived by multiplying the modified carbon accumulation layer by pixel area, converting the units from MgC ha⁻¹ yr⁻¹ to MgC per pixel per year. This enabled a straightforward summation of pixel values to estimate national and global carbon accumulation. Although the analysis was conducted in units of carbon, results are reported in terms of carbon dioxide by applying a molecular weight conversion factor of 44/12 (CO₂/C).

Data availability

The global HVFE maps, delineated under both minimum and maximum scenarios at 30-m resolution, are available via Zenodo at <https://doi.org/10.5281/zenodo.15338535> (ref. 51). All input datasets used to develop the HVFE maps and carbon removal estimates are publicly available from their respective original sources, as referenced in Methods and Supplementary Information. Country-level outputs for both water and carbon components—including the data used to generate key figures—are provided in CSV format and are available via GitHub at <https://github.com/MahyaSad/Global-High-Value-Freshwater-Ecosystem>.

Code availability

The Python code used to generate the global HVFE map and to produce country-level freshwater and carbon estimates is available via GitHub at <https://github.com/MahyaSad/Global-High-Value-Freshwater-Ecosystem>. Code development was conducted primarily in Python (v3.9.15; <https://www.python.org/>) for HVFE mapping, freshwater analysis and figure generation. Carbon estimation was performed using Google Earth Engine (<https://earthengine.google.com/>).

References

1. Lynch, A. J. et al. People need freshwater biodiversity. *WIREs Water* **10**, e1633 (2023).
2. Damania, R., Desbureaux, S., Rodella, A.-S., Russ, J. & Zaveri, E. *Quality Unknown: The Invisible Water Crisis* (World Bank Publications, 2019).
3. Grill, G. et al. Mapping the world's free-flowing rivers. *Nature* **569**, 215–221 (2019).
4. *Bending the Curve of Biodiversity Loss* (WWF, 2020).
5. Calvin, K. et al. *Climate Change 2023: Synthesis Report* (IPCC, 2023); <https://doi.org/10.59327/IPCC/AR6-9789291691647>.
6. *The United Nations World Water Development Report 2020: Water and Climate Change* (UNESCO, 2020).
7. *Global Solar UV Index: A Practical Guide* (World Health Organization, World Meteorological Organization, UNEP, International Commission on Non-Ionizing Radiation Protection, 2002).
8. Mekonnen, M. M. & Hoekstra, A. Y. Four billion people facing severe water scarcity. *Sci. Adv.* **2**, e1500323 (2016).
9. National Adaptation Plans (NAPs): overview and guidelines. *UNFCCC* <https://unfccc.int/topics/adaptation-and-resilience/workstreams/national-adaptation-plans> (2024).
10. Water in the nationally determined contributions: increasing ambition for the future. *UNDP-SIWI Water Governance Facility* <https://siwi.org/publications/water-in-the-nationally-determined-contributions-increasing-ambition-for-the-future/> (2023).
11. Pilla, R. M. et al. Anthropogenically driven climate and landscape change effects on inland water carbon dynamics: what have we learned and where are we going?. *Glob. Change Biol.* **28**, 5601–5629 (2022).
12. Prairie, Y. T. et al. Greenhouse gas emissions from freshwater reservoirs: what does the atmosphere see?. *Ecosystems* **21**, 1058–1071 (2018).
13. Cook-Patton, S. C. et al. Mapping carbon accumulation potential from global natural forest regrowth. *Nature* **585**, 545–550 (2020).
14. Veldman, J. W. et al. Where tree planting and forest expansion are bad for biodiversity and ecosystem services. *BioScience* **65**, 1011–1018 (2015).
15. Common guidance for the identification of high conservation values (amended version). *HCV Network* <https://www.hcvnetwork.org/library/common-guidance-for-the-identification-of-hcv-english-indonesian-french-portuguese> (2017).
16. Moberg, T. et al. *Designing and Managing Protected and Conserved Areas for Inland Water Ecosystems and Biodiversity* (IUCN World Commission on Protected Areas, 2024).
17. Potapov, P. et al. The global 2000–2020 land cover and land use change dataset derived from the Landsat archive: first results. *Front. Remote Sens.* **3**, 856903 (2022).
18. Amatulli, G. et al. Hydrography90m: a new high-resolution global hydrographic dataset. *Earth Syst. Sci. Data* **14**, 4525–4550 (2022).
19. Nardi, F., Annis, A., Di Baldassarre, G., Vivoni, E. R. & Grimaldi, S. GFPLAIN250m, a global high-resolution dataset of Earth's floodplains. *Sci. Data* **6**, 180309 (2019).
20. Sutfin, N. A., Wohl, E. E. & Dwire, K. A. Banking carbon: a review of organic carbon storage and physical factors influencing retention in floodplains and riparian ecosystems. *Earth Surf. Process. Landf.* **41**, 38–60 (2016).
21. Clifton, B., Ghezzehei, T. A. & Viers, J. H. Carbon stock quantification in a floodplain restoration chronosequence along a Mediterranean-montane riparian corridor. *Sci. Total Environ.* **946**, 173829 (2024).
22. Pörtner, H.-O. et al. *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ. Press, 2022).
23. *Nationally Determined Contributions under the Paris Agreement* (UNFCCC, 2024); <https://unfccc.int/documents/641792>
24. Ingemarsson, M. L., Weinberg, J., Rudebeck, T., & Wang-Erlandsson, L. The essential drop to reach net-zero: unpacking freshwater's role in climate change mitigation. <https://siwi.org/publications/essential-drop-to-net-zero/> (2022).
25. Aqueduct country rankings. *World Resources Institute* <https://www.wri.org/applications/aqueduct/country-rankings/> (2024).

26. *Revised Pakistan 2022 Floods Response Plan Final Report* (United Nations Office for the Coordination of Humanitarian Affairs, 2023); <https://reliefweb.int/report/pakistan/revised-pakistan-2022-floods-response-plan-final-report-issued-15-dec-2023>
27. Brauman, K. A., Daily, G. C., Duarte, T. K. & Mooney, H. A. The nature and value of ecosystem services: an overview highlighting hydrologic services. *Annu. Rev. Environ. Resour.* **32**, 67–98 (2007).
28. *National Water Resources Policy 2020* (Government of Nepal, Ministry of Energy, Water Resources and Irrigation, 2020).
29. Sharma, B. et al. *Springs, Storage Towers, and Water Conservation in the Midhills of Nepal. ICIMOD Working Paper 2016/3* (International Centre for Integrated Mountain Development, 2016); <https://hdl.handle.net/10568/90599>
30. OECMs Booklet – Nepal (Ministry of Forests and Environment, Nepal, 2023).
31. Shreevastav, B. B., Tiwari, K. R., Mandal, R. A. & Nepal, A. Assessing flood vulnerability on livelihood of the local community: a case from southern Bagmati corridor of Nepal. *Prog. Disaster Sci.* **12**, 100199 (2021).
32. Kamb, J.-C. T., Sisa, E. M., Pwema, V. K., Schie'Nkung'Mutambel'Hytis, D. & Lohaka, J. D. Evaluation of the state of riparian ecosystems in the city of Kinshasa by the quality of riparian strips: the case of the Bumbu River (DR Congo). *Int. J. Sci. Res. Arch.* **6**, 113–124 (2022).
33. Shumway, C. et al. *Biodiversity Survey: Systematics, Ecology, and Conservation along the Congo River*. Research report for the Congo River Environment and Development Project (New England Aquarium, 2003).
34. Abulu, L. & Sutherland, L. *Indigenous Groups Unveil Plan to Protect 80% of the Amazon in Peru and Ecuador* (Mongabay, 2021).
35. Monterroso, I., Cronkleton, P., Pinedo, D. & Larson, A. M. *Reclaiming Collective Rights: Land and Forest Tenure Reforms in Peru (1960–2016)* Vol. 224 (CIFOR, 2017).
36. Ashraf, I., Ahmad, S. R., Ashraf, U. & Khan, M. Community perspectives to improve flood management and socio-economic impacts of floods at Central Indus River, Pakistan. *Int. J. Disaster Risk Reduct.* **92**, 103718 (2023).
37. Euliss, N. H., Smith, L. M., Wilcox, D. A. & Browne, B. A. Linking ecosystem processes with wetland management goals: charting a course for a sustainable future. *Wetlands* **28**, 553–562 (2008).
38. Eilander, D. et al. Modeling compound flood risk and risk reduction using a globally applicable framework: a pilot in the Sofala province of Mozambique. *Nat. Hazards Earth Syst. Sci.* **23**, 2251–2272 (2023).
39. Biggs, T. W., Santiago, T. M. O., Sills, E. & Caviglia-Harris, J. The Brazilian Forest Code and riparian preservation areas: spatiotemporal analysis and implications for hydrological ecosystem services. *Reg. Environ. Change* **19**, 2381–2394 (2019).
40. Soares-Filho, B. et al. Cracking Brazil's Forest Code. *Science* **344**, 363–364 (2014).
41. Roe, S. et al. Land-based measures to mitigate climate change: Potential and feasibility by country. *Glob. Change Biol.* **27**, 6025–6058 (2021).
42. Friedlingstein, P. et al. Global Carbon Budget 2022. *Earth Syst. Sci. Data* **14**, 4811–4900 (2022).
43. Schuster, L., Taillardat, P., Macreadie, P. I. & Malerba, M. E. Freshwater wetland restoration and conservation are long-term natural climate solutions. *Sci. Total Environ.* **922**, 171218 (2024).
44. Kayranli, B., Scholz, M., Mustafa, A. & Hedmark, Å. Carbon storage and fluxes within freshwater wetlands: a critical review. *Wetlands* **30**, 111–124 (2010).
45. Nahlik, A. M. & Fennessy, M. S. Carbon storage in US wetlands. *Nat. Commun.* **7**, 13835 (2016).
46. Abood, S. A.; Spencer, L.; Wieczorek, M. U.S. Forest Service national riparian areas base map for the conterminous United States in 2019. Fort Collins, CO. Forest Service Research Data Archive <https://doi.org/10.2737/RDS-2019-0030> (2022).
47. Lane, C. R. et al. Mapping global non-floodplain wetlands. *Earth Syst. Sci. Data* **15**, 2927–2955 (2023).
48. Dinerstein, E. et al. An ecoregion-based approach to protecting half the terrestrial realm. *BioScience* **67**, 534–545 (2017).
49. Potapov, P. et al. Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. *Nat. Food* **3**, 19–28 (2021).
50. Sprenkle-Hyppolite, S., Griscom, B., Griffey, V., Munshi, E. & Chapman, M. Maximizing tree carbon in croplands and grazing lands while sustaining yields. *Carbon Balance Manag.* **19**, 23 (2024).
51. Ghazi Zadeh Hashemi, M. et al. 30-meter high-value freshwater ecosystems (HVFEs) dataset. Zenodo <https://doi.org/10.5281/zenodo.1533853> (2025).
52. Savin, I., King, L. C. & van den Bergh, J. Analysing content of Paris climate pledges with computational linguistics. *Nat. Sustain.* **8**, 297–306 (2025).

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Author contributions

M.G.Z.H., K.S., I.N.M., J.D.B., M.O.B., V.G. and S.S.-H. conceptualized the study. M.G.Z.H. developed the HVFE maps. M.G.Z.H., K.S. and V.G. designed and carried out the statistical analyses. M.G.Z.H., K.S. and V.G. designed the visual materials and cowrote the paper. All authors reviewed, edited and contributed to the discussion.

Competing interests

The authors declare no competing interests.

Additional information

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